SUSY AND THE DECAY $H_2^0 \to gg$ *

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ABSTRACT

In this talk I present a detailed SUSY QCD calculation of the decay rate of the lightest Higgs boson H_2^0 into two gluons, where all quarks and scalar quarks are taken within the relevant loop diagrams. I include the mixing of all the three generations of the scalar partners of the left and right handed quarks and show that their contribution is comparable to the quark contribution in the MSSM for small values of the soft SUSY breaking parameter m_S. Furthermore in the MSSM the contribution from the bottom quark becomes as large as the top quark contribution for large $\tan\beta$ and large Higgs masses. As a result, the two gluon decay rate of H_2^0 is much larger than the two gluon decay rate of an equal mass standard model Higgs boson. I further compare the decay mode of $H_2^0 \to gg$ to the similar decay modes of $H_2^0 \to c\bar{c}$ including one loop QCD corrections and show that in some cases $\Gamma(H_2^0 \to gg)$ is even higher than $\Gamma(H_2^0 \to c\bar{c})$.

1. Introduction

The Higgs boson is the last particle in the standard model (SM), which yet lacks any experimental evidence. Its discovery therefore is of great importance. The instruments of discovery will be LEP if the Higgs mass is smaller than the Z boson mass and LHC for higher masses. While for a Higgs mass smaller than twice of the gauge boson mass the most important decay modes for its discovery will be $H \to q\bar{q}$ (here $q = c, b$) and $H \to \gamma\gamma$ and to some extent $H \to gg$, it will be the decay into two W or Z bosons for higher masses of the Higgs boson.

It is well known that the SM is not a sufficant model when considering unification theories. The favourite model beyond the SM is its minimal supersymmetric extension (MSSM) [1]. The content of Higgs particles in the MSSM is quite different than the one of the SM: it contains two scalar Higgs bosons H_1^0, H_2^0, one pseudo-scalar H_3^0 and one charged scalar $H^\pm$. The most important point is that the mass of the lightest Higgs particle $m_{H_2^0}$ has to be smaller than the Z boson mass at tree level and is enhanced to a maximum value of around 130 GeV when loop corrections are included [2], thus making a SUSY Higgs boson more experimentally reachable.

For a Higgs boson far less massive than the Z boson, the $H_2^0 \to \gamma\gamma$ is the most important decay mode and was analyzed in [3] (for the SM) and in [4] (for the MSSM). For values of the Higgs mass up to twice the W and Z boson masses the decays $H_2^0 \to q\bar{q}$ and $H_2^0 \to gg$ will become more important. The QCD corrections to the first decay mode within the SM were considered in [5] (and references therein) and within the MSSM in [6]. The second decay mode was considered in [7] and two loop QCD corrections within the SM were considered in [8] and found to be

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relatively large: about 60%. In this talk I show that the MSSM leads to a much higher Higgs into two gluons decay rate than the SM for some supersymmetric parameters, making this decay mode more interesting.

It will be difficult to measure $\Gamma(H_2^0 \to gg)$ due to QCD jet background, although it might be experimental measurable at future e^+e^-- colliders [9]. Therefore it is important to consider all kind of models in regards to this decay mode and as I will show the scalar quarks contribution can be several tens of per cent compared to the quark contribution and also to the $H_2^0 \to c\bar{c}$ decay rate for some SUSY parameter space after summing over all scalar quarks.

In the next section I present the results and discuss them in the third section. In the calculation I include the mixing of all scalar partners of the left and right handed quarks, which is expected to be of importance in the top quark sector due to the high top quark mass of 180 GeV reported by the CDF and $D\emptyset$ groups [10]. In the bottom quark sector I also include one loop effects. As a surprise I also find, that the mixing is not negligible in the charm and strange quark sector independant of the value for $\tan\beta$, the ratio of the Higgs vacuum expectation values (vev's). In this talk I only present the results and refer the interested reader for detailed calculations to [11].

2. SUSY QCD Corrections to $H_2^0 \to gg$

In the MSSM there are strong relations among the masses and mixing angles of the Higgs bosons. Given two values e.g. $\tan\beta = v_2/v_1$ (the ratio of the vacuum expectation values) and the light Higgs boson mass $m_{H_2^0}$ all the other masses and angles including one loop corrections can be obtained analytically as presented in [11].

In the SM the decay mode of the Higgs boson into two gluons occur via one loop diagrams with all quarks taken within the loop as shown in Fig.1. The final amplitude is finite and the result is given by:

$$iM_q = + g_2 \frac{g_s^2}{(4\pi)^2} \frac{m_Z^2}{m_W} \frac{4}{q^2} (p_1 p_2 g_{\alpha\beta} - p_{1\beta} p_{2\alpha}) \epsilon_{p_1}^{*\alpha} \epsilon_{p_2}^{*\beta} T_q \tag{1}$$

$$T_q = \sum_q \frac{m_q^2}{m_Z^2} K^{qH_2^0} [2 - (1 - 4\lambda_q) I_q]$$

with $q^2 = m_{H_2^0}^2$ on mass shell and $K^{uH_2^0} = \cos\alpha/\sin\beta$ and $K^{dH_2^0} = -\sin\alpha/\cos\beta$ and the function I_q defined by

$$I_q = \begin{cases} -2[\arcsin(\frac{1}{2\sqrt{\lambda_q}})]^2, & 1/4 \leq \lambda_q \\ [\ln(\frac{r_+}{r_-})^2 - \pi^2]/2 + i\pi \ln(\frac{r_+}{r_-}), & \lambda_q < 1/4 \end{cases} \tag{2}$$

$$r_\pm = 1 \pm (1 - 4\lambda_q)^{\frac{1}{2}}$$

with $\lambda_q = (m_q/m_{H_2^0})^2$. Before I present the results of the scalar quarks contribution to the Higgs decay into two gluons I first want to comment on their mass matrices in the MSSM. The mixing term of the scalar partners of the left and right handed quarks is proportional to the quark masses and hence was neglected before the top quark was discovered as very heavy. In the calculation here I include the mixing of all scalar quarks and present the result in their mass eigenstates, that is instead of the current eigenstates $\tilde{q}_{L,R}$ I work with the mass eigenstates

$$\tilde{q}_1 = cos\Theta_q \tilde{q}_L + \sin\Theta_q \tilde{q}_R \qquad \tilde{q}_2 = -\sin\Theta_q \tilde{q}_L + \cos\Theta_q \tilde{q}_R \tag{3}$$

Here q stands for all three generations of the scalar up and scalar down quarks. A detailed description of their mass matrices including one loop corrections for the scalar down quarks is presented in [11]. In the calculation it turns out that the mixing of the first generation is negligible as expected, whereas in the second generation $sin\Theta_q \simeq 0.1 - 0.5$ (the last value only for $\tan\beta \gg 1$) and therefore not negligible. In the third generation $\sin\Theta_q \simeq 1/\sqrt{2}$ due to the heavy top quark mass. For the scalar bottom quark the mixing angle only becomes that big when $\tan\beta \gg 1$.

Fig.1: The penguin diagram with up and down quarks within the loop

Fig.2: The penguin diagrams with scalar up and down quarks within the loop

In the MSSM we have to add up the two diagrams shown in Fig.2. After summation the amplitude is finite and the result is given by:

$$iM_{\tilde{q}} = -\frac{g_2}{\cos\Theta_W}\frac{g_s^2}{(4\pi)^2}\frac{4m_Z}{q^2}(p_1 p_2 g_{\alpha\beta} - p_{1\beta}p_{2\alpha})\epsilon_{p_1}^{*\alpha}\epsilon_{p_2}^{*\beta}T_{\tilde{q}} \tag{4}$$

$$T_{\tilde{q}} = \sum_q \left\{ [\cos^2\Theta_q K_{11}^{\tilde{q}H_2^0} + \sin^2\Theta_q K_{22}^{\tilde{q}H_2^0} + 2\sin\Theta_q\cos\Theta_q K_{12}^{\tilde{q}H_2^0}](1 + 2\lambda_{\tilde{q}_1}I_{\tilde{q}_1}) \right.$$

$$\left. + [\sin^2\Theta_q K_{11}^{\tilde{q}H_2^0} + \cos^2\Theta_q K_{22}^{\tilde{q}H_2^0} - 2\sin\Theta_q\cos\Theta_q K_{12}^{\tilde{q}H_2^0}](1 + 2\lambda_{\tilde{q}_2}I_{\tilde{q}_2}) \right\}$$

$$K_{11}^{\tilde{u}H_2^0} = -(\frac{1}{2} - e_u s_W^2)\sin(\alpha + \beta) + \left(\frac{m_u}{m_Z}\right)^2\frac{\cos\alpha}{\sin\beta}$$

$$K_{22}^{\tilde{u}H_2^0} = -e_u s_W^2\sin(\alpha + \beta) + \left(\frac{m_u}{m_Z}\right)^2\frac{\cos\alpha}{\sin\beta}$$

$$K_{12}^{\tilde{u}H_2^0} = K_{21}^{\tilde{u}H_2^0} = \frac{1}{2}\frac{m_u}{m_Z^2}\frac{1}{\sin\beta}(A_u\cos\alpha + \mu\sin\alpha)$$

$$K_{11}^{\tilde{d}H_2^0} = (\frac{1}{2} + e_d s_W^2)\sin(\alpha + \beta) - \left(\frac{m_d}{m_Z}\right)^2\frac{\sin\alpha}{\cos\beta}$$

$$K_{22}^{\tilde{d}H_2^0} = -e_d s_W^2\sin(\alpha + \beta) - \left(\frac{m_d}{m_Z}\right)^2\frac{\sin\alpha}{\cos\beta}$$

$$K_{12}^{\tilde{d}H_2^0} = K_{21}^{\tilde{d}H_2^0} = -\frac{1}{2}\frac{m_d}{m_Z^2}\frac{1}{\cos\beta}(A_d\sin\alpha + \mu\cos\alpha)$$

with $s_W^2 = \sin^2\Theta_W$ and again $q^2 = m_{H_2^0}^2$ on mass shell. Note that the non diagonal terms $K_{12}^{\tilde{q}H_2^0}$ in $T_{\tilde{q}}$ only contribute when the scalar mass eigenstates differ, which

mainly is the case for the third generation. Note also that $T_{\tilde{q}}$ is identical to 0 if all scalar quarks have equal masses. The amplitudes in eq.(1) and eq.(4) lead to the following decay rate:

$$\Gamma(H_2^0 \to gg) = \frac{\alpha \alpha_s^2}{8\pi^2 \sin^2 \Theta_W \cos^2 \Theta_W} \frac{m_Z^2}{m_{H_2^0}} |T_q - T_{\tilde{q}}|^2 \qquad (5)$$

If $T_{\tilde{q}}$ is set to 0 eq.(5) reproduce eq.(2.29) given in [12].

In the next section I will discuss the results of the lightest supersymmetric Higgs boson into two gluons decay rate obtained in eq.(8).

3. Discussions

To see how big the contribution of the scalar quarks compared to the quarks is I plot in Fig.3 the ratio $\Gamma^{\tilde{q}+q}/\Gamma^q$ of the decay rate $\Gamma(H_2^0 \to gg)$ as function of the soft SUSY breaking scalar mass m_S for a fixed value of $\mu = 250$ GeV, the bilinear Higgs mass term, and two different values of the Higgs mass $m_{H_2^0} = 60$ GeV and 120 GeV and three different values of $\tan\beta = 3$ (solid line), 10 (dashed line) and 60 (dotted line). Higher values of $\tan\beta$ are preferred in superstring inspired E_6 and $SO(10)$ models. For Γ^q and $\Gamma^{\tilde{q}+q}$ I have taken T_q as given in eq.(2) with the couplings $K^{qH_2^0}$, that is including the large enhancements (relative to the SM) due to large $\tan\beta$. As a result I have that for small values of m_S the scalar quarks contribute even more than the quarks, although their contribution decrease rapidly and remains only a few per cent for $m_S > 600$ GeV. For $\tan\beta = 60$ the scalar quarks contribution diminishes the ratio for $m_S < 350$ GeV and enhances it for higher values. The influence of μ is very small for small $\tan\beta$ and becomes more important for very high $\tan\beta$ values. For small values of $\tan\beta$ higher values of μ enhance the decay rate a little bit. For high values of $\tan\beta$ it is the other way around and the differences are larger. A negative value for μ leads to a bit smaller values of the decay rate.

Fig.3: The ratio of $\Gamma^{\tilde{q}+q}/\Gamma^q$ as explained in text. Except for $\tan\beta = 3$ the upper curves are for $m_{H_2^0} = 60$ GeV.

Fig.4: The ratios of $\Gamma^{\tilde{q}+q}/\Gamma^q$ and $\Gamma^{\tilde{q}+q}/\Gamma^{c\bar{c}}$ for $m_{H_2^0} = 60$ GeV as explained in text.

In Fig.4 I have plotted the ratio of the Higgs into two gluons decay rate of the MSSM compared to the SM, that is $\Gamma^{\tilde{q}+q}/\Gamma^q$, where I have taken Γ^q as it is in the SM

that is without the couplings $K^{qH_2^0}$, whereas I included them in $\Gamma^{\tilde{q}+q}$. For the Higgs mass I have taken 60 GeV. As a result I have that for scalar masses smaller than 500 GeV the Higgs into two gluons decay rate is enhanced by several tens of per cents in the MSSM and gives the same result than the SM for higher values of the scalar masses. As in Fig.3 for $\tan\beta = 60$ and $m_S < 350$ GeV the decay is diminished.

In Fig.5 I have done the same as in Fig.4 but for a Higgs mass of $m_{H_2^0} = 120$ GeV. Here the results are quite different than in Fig.4. For $\tan\beta = 3$ and $m_S \geq 600$ GeV the pseudo Higgs obtains a negative mass squared. For $\tan\beta = 10$ the same happens for a small region when $m_S \approx 650$ GeV. As a result I have that in the MSSM the Higgs into two gluon decay rate is enhanced by several tens of per cent for $\tan\beta = 3$, by a factor of $2-3$ for $\tan\beta = 10$ and $m_S < 300$ GeV and even by an order of magnitude for $\tan\beta = 60$ with the highest contribution for a scalar mass around 550 GeV.

As I have shown in Fig.3 the scalar quarks decouples for $m_S > 600$ GeV. The reason why the branching ratio as shown in Fig.5 is still larger than 1 even for higher values of the scalar mass is that Γ^q is quite different in the MSSM with the couplings $K^{qH_2^0}$ than it is in the SM without these couplings. In the SM the main contribution is from the heavy top quark and a few per cent from the bottom quark. The contribution of the other quarks are negligible due to their small masses. In the MSSM the bottom quark contribution becomes as important as the top quark contribution for large $\tan\beta$ values eg. the ratio $\Gamma^q_{SM}/\Gamma^q_{MSSM}$ becomes very small depending on the size and sign of $\sin\alpha$, which becomes relative large around ±0.5 and thus leading to large values of $\Gamma^{\tilde{q}+q}/\Gamma^q$ as seen in Fig.5. For a small Higgs mass of 60 GeV as I have taken in Fig.4 $\sin\alpha$ remains always smaller than around -2×10^{-2} and therefore keeps the bottom quark mass contribution as small as in the SM.

Some curves in Fig.4–5 start at different values of m_S because, for values of m_S higher than 600 GeV I obtain an unphysical negative mass squared for the pseudo particle H_3^0 if $\tan\beta = 3$; for $\tan\beta = 10$ the unphysical region is when $m_S \simeq 650$ GeV; whereas for $\tan\beta = 60$ $m_{H_3^0}$ is physical for all m_S.

Fig.5: The same as in Fig.4 with $m_{H_2^0} = 120$ GeV. The upper curves are for $\Gamma^{\tilde{q}+q}/\Gamma^{c\bar{c}}$.

Fig.6: The same as Fig.4 but as a function of $m_{H_2^0}$. The upper curves at the higher Higgs masses. are for $\Gamma^{\tilde{q}+q}/\Gamma^{c\bar{c}}$.

A negative eigenvalue of the scalar bottom quark mass also occurs if $m_S < 200$ GeV for $\tan\beta = 3$ and 10 or $m_S < 300$ GeV for $\tan\beta = 60$. Here the parameter c, which

enters in the one loop corrections to the scalar down quark masses, is of importance, neglecting it would allow us to use m_S as small as 100 GeV (for $\tan\beta = 3$) without running into one negative mass eigenvalue of the scalar bottom quark mass, with the result that $\Gamma^{\tilde{q}+q}$ can become much larger than Γ^q. Unfortunately even for smaller values for $c \simeq -0.5$ I obtain negative values with such a small scalar mass. Since c cannot be neglected when including loop corrections I excluded those regions in the figures.

In Fig.4 and Fig.5 I also have plotted the ratio of the decay rates $\Gamma(H_2^0 \to gg)/\Gamma(H_2^0 \to c\bar{c})$. For the decay rate $\Gamma(H_2^0 \to b\bar{b}, c\bar{c})$ I used the tree result including the SM QCD corrections as given in eq.(8) of Ref. [5] with the changes of the tree level couplings within the MSSM. I did not include the SUSY QCD correction, because they are far smaller than the SM QCD correction as I have shown in [6]. There I showed that for $\tan\beta = 1$ SUSY QCD corrections do not contribute at all to this decay mode $(\sin(\alpha + \beta) = 0)$ and presented the results in the limit of $\tan\beta \gg 1$. There I did not include the mixing of the scalar charm and bottom quarks, but since $m_{\tilde{c}_1} \approx m_{\tilde{c}_2}$ even a large mixing angle will not change the results for the decay rate $\Gamma(H_2^0 \to c\bar{c})$ presented there. This might not be true for $\Gamma(H_2^0 \to b\bar{b})$ which I did not consider here since it is much higher than $\Gamma(H_2^0 \to gg)$, by a factor of at least 50. Therefore in Fig.4 and Fig.5 I only compared the Higgs into two gluons decay rate with the one to the charm- anti-charm quarks. In Fig.4, the dependence of the ratio to the scalar mass m_S is very small, since $\Gamma^{\tilde{q}+q}$ becomes very small and the dependence of $\Gamma^{c\bar{c}}$ to m_S is only via the angles $\cos^2\alpha/\sin^2\beta$, which is compensated by the $K^{tH_2^0}$ coupling in the T_q term. For a very large scalar mass the ratio remains constant with a value of around 0.31 independant of $\tan\beta$. A quite different result I obtain in Fig.5, especially again for $\tan\beta = 60$, for the same reason as explained above. The shape of the figures is quite similar compared to the ratio $\Gamma^{\tilde{q}+q}/\Gamma^q$. For scalar masses much higher than 1 TeV the ratio remains constant with a value of around 1 independant of $\tan\beta$.

Finally in Fig.6 I show the influence of the Higgs mass to the decay rate $\Gamma(H_2^0 \to gg)$ for a fixed value of $\mu = 250$ GeV and $m_S = 300$ GeV and three different values of $\tan\beta = 3, 10$ and 60. In the case $\tan\beta = 3$ I obtain negative values for the mass squared of the pseudo Higgs H_3^0 in the range of $95 < m_{H_2^0} < 105$ GeV which therefore has to be excluded. As a result I have that $\Gamma^{\tilde{q}+q}/\Gamma^q$ is weakly dependant of the Higgs mass, not so $\Gamma^{\tilde{q}+q}/\Gamma^{c\bar{c}}$, which shape is basically dominated by $\cos\alpha$ and $\sin\beta$.

4. Conclusion

In this talk I presented the corrections to the lightest MSSM Higgs boson decay into two gluons when scalar quarks are taken within the loop. I included in my calculation the mixing of all scalar quarks although it only becomes important for the second and third generation. I have shown that scalar quarks lead to a decay rate of the same order as the quarks in the SM for values of m_S smaller than 600 GeV. In the SM the largest contribution comes from the top quark due to the m_q^2 in T_q. In the MSSM the $T_{\tilde{q}}$ are of the same order for all scalar quarks and therefore contribute many more terms to $\Gamma(H_2^0 \to gg)$ than the SM alone. Furthermore in the MSSM the T_q can become much larger than in the SM for $\tan\beta \gg 1$ and large negative or positive $\sin\alpha$. I also have shown that the Higgs into two gluon decay rate can become even larger than the decay into charm- anti-charm quarks for $\tan\beta = 3$ and the Higgs mass larger than around 80 GeV and for $\tan\beta = 10$ and 60 and the

Higgs mass larger than the Z boson mass, but still remains more than a factor of 50 smaller than its decay into bottom- anti-bottom quarks.

Although the decay of the Higgs into two gluons will be difficult to measure it is of importance to know how big the influence of models beyond the SM might be. Furthermore it might be measurable at future e^+e^- colliders [9]. The amplitudes given here can also be used when considering Higgs production in hadron colliders via gluon fusion with following decay in heavy leptons [13].

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